A 2 Megawatt Multi-Stage Proton Accumulator

1 Introduction

1.1 Motivation

The delivery of high intensity proton beams for neutrino experiments is a core element of the Fermilab physics program for the next decade and beyond. This document outlines a plan which will greatly enhance the intensity capability beyond the year 2010 should budget and approval for the Proton Driver Linac fail to materialize. In order to reduce costs and to minimize disruption to the ongoing program, the plan uses existing infrastructure (tunnel enclosures, service buildings, power, utilities, etc.). The cost scale is estimated to be less than $100M, and the plan could be fully implemented by 2012 without the need for an extended shutdown period.

The use of existing infrastructure allows the plan to be broken into stages. Project staging has the important benefit of providing a fraction of the total performance at a fraction of the total cost. The schedule for each stage is driven by physics need and funding availability.

1.2 Concept

Multi-turn injection into the Booster is the current process for obtaining high intensity proton bunches in the Main Injector for neutrino experiments. Because of the relatively small aperture of the Booster and the large space charge tune shift at Booster injection, proton loss at injection limits the number of protons per bunch. Since space charge effects rapidly decrease with energy, it is more desirable to increase the proton intensity at higher energies. Due to the rapid cycling nature of the Booster, many Booster batches can be quickly combined at the Booster extraction energy. Because the bunch length requirements for neutrino experiments are not strict, the best technique to combine multiple Booster batches is to coalesce them longitudinally.

Slip stacking multiple Booster batches is the central concept of the Proton Plan[1]. In Stage 1, while the collider program is still running, nine Booster batches will be slipped stacked in the Main Injector for the neutrino program. In Stage 2, when the Recycler becomes available after the collider program is concluded, the slip stacking will be done in the Recycler which can handle 33% more batches with a 30% decrease in the cycle time. The number of batches stacked into the Recycler can not be increased further by slip stacking because of the rather severe amount of emittance dilution that is fundamental to the slip stacking process.

Another large increase in proton intensity is possible after the collider program concludes because the present antiproton production complex can be converted into a multi-stage proton accumulator for injection into the Main Injector. This accumulator would have three major components, each re-using or replacing existing machines:

- The Accumulator ring as a RF momentum stacker.
- The Recycler ring as a box-car stacker.
- The Debuncher ring would be replaced with a wide aperture booster.

1.2.1 RF Momentum Stacking in the Accumulator

The center piece of this concept is RF momentum stacking in the Accumulator. The key features of RF momentum stacking are a large momentum aperture and injection system located at high dispersion. Because the same features are required for stochastic momentum stacking of antiprotons, RF momentum stacking in the Accumulator would be possible with only minor modifications to the Accumulator.

During momentum stacking, a Booster batch is placed on the injection orbit of the Accumulator and accelerated towards the high energy aperture as shown in Figure 1-1. Another Booster batch is injected onto the injection orbit and accelerated towards the high energy aperture and deposited adjacent to the previous batch. The limit to how many Booster batches can be stacked is not the Accumulator aperture but the momentum aperture of the Main Injector at the transition energy. With present Booster performance, the Main Injector momentum aperture can comfortably handle over four Booster batches. This large number of batches can be combined using momentum stacking because momentum stacking has very little longitudinal emittance dilution.

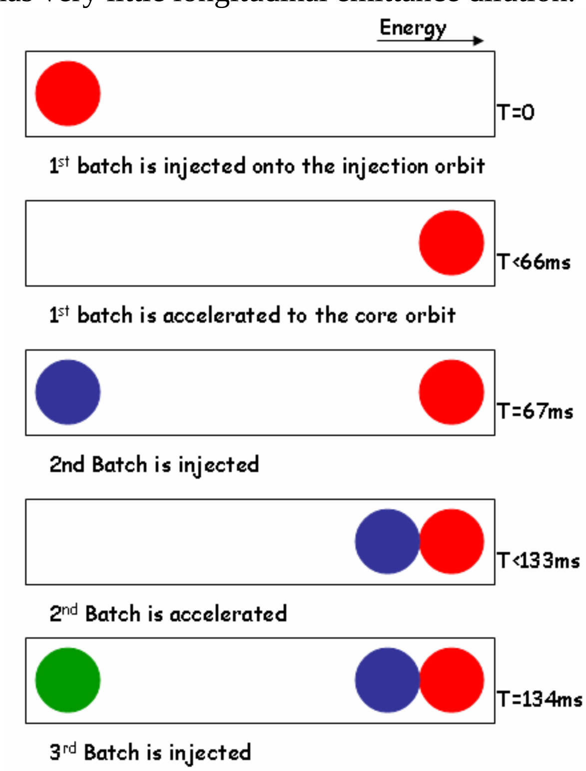

Figure 1-1 Cross-section of the transverse aperture in high dispersion of the Accumulator during momentum stacking.

1.2.2 Box Car Stacking in the Recycler

Once at least three to four Booster batches have been momentum stacked in the Accumulator, the coalesced proton stack would be transferred to the Recycler. Since the Accumulator circumference is one seventh of the Recycler circumference, five more Accumulator stacks can be placed one after the other in the Recycler (box-car style) while leaving one seventh of the ring as an abort gap. The Recycler fully loaded in this manner would contain twenty four Booster batches which is twice the number of batches of Stage 2 in the Proton Plan. The lack of accelerating cavities in the Recycler and the low impedance Recycler beam chamber make the Recycler an ideal ring to store large amounts of beam current. The Recycler is loaded while the Main Injector is ramping and delivering 120 GeV beam as shown in Figure 1-2. Once the Main Injector has returned to the injection energy, it is re-loaded from the Recycler in a single turn and begins accelerating immediately. To load twenty four batches at a 15 Hz repetition rate would require 1.6 seconds which matches the Main Injector cycle time.

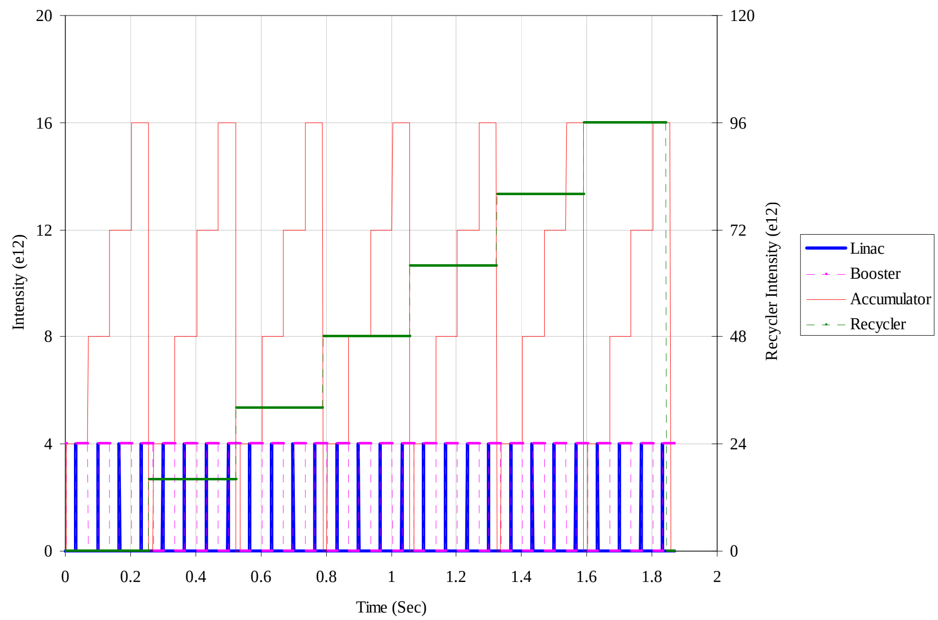

Figure 1-2 Accelerator Time line for momentum stacking in the Accumulator and box-car stacking in the Recycler

2 Stages of the Proton Plan

The Proton Accumulator is best thought of as extended stages of the present Proton Plan. The extended Proton Plan would have four stages beyond present operating conditions. The schedule for each stage is driven by physics need and funding availability. While project staging might not be the quickest way to implement a project, it has the distinct advantage of providing a fraction of the total performance at a fraction of the total cost. This is in comparison to a large construction project in which no benefit is reaped until a significant amount of the project resources have been spent.

2.1 Present Operations

The circumference of the Main Injector is seven times the Booster circumference. However, to provide enough space for an abort gap, only 6/7 of the ring is available for beam. During present operations two Booster batches are slip-stacked in the Main Injector for antiproton production for the collider. Five Booster batches are box-car stacked for the 120 GeV neutrino program (NuMI). The remaining available Booster throughput is sent to the Booster 8 GeV Neutrino program (BNB). In Mixed-Mode operations, the two antiproton production batches and the five NuMI batches are accelerated in the Main Injector at the same time. Loading the seven batches in the Main

Injector at 15 Hz requires 0.47 seconds. With the Main Injector ramp length at 1.5 seconds, the resulting minimum cycle time is 2 seconds.

However, the rate of antiproton production must slow down as the antiproton stack size grows[2]. The reduction in antiproton stacking rate is achieved by a combination of lengthening the Main Injector cycle time and interleaving NUMI only cycles with Mixed-Mode cycles. The average cycle time is about 2.2 seconds.

Because of tunnel activation, beam loss during the Booster acceleration cycle presently limits the Booster throughput to about 6.6×10^{16} protons per hour. Antiproton production requires two batches of 4.2×10^{12} protons every 3 seconds on average. The 120 GeV neutrino program (NuMI) requires five batches of 5.0×10^{12} protons every 2.2 seconds on average. As shown in Table 2-1, the NuMI beam power is about 220kW and the Booster 8 GeV Neutrino program gets about 1.5×10^{16} protons per hour.

	Present	Stage 1	Stage 2	Stage 3	Stage 4	
Booster Flux	6.6	13.5	13.5	21.6	43.2	$\times 10^{16}$ pph
Collider Flux	1.0	1.4	0.0	0.0	0.0	$\times 10^{16}$ pph
BNB Flux	1.5	4.1	0.0	0.0	0.0	$\times 10^{16}$ pph
NuMI Flux	4.1	8.1	13.5	21.6	43.2	$\times 10^{16}$ pph
NuMI Power	218	432	722	1152	2304	kW

Table 2-1

2.2 Stage 1

The first stage is the currently funded Proton Plan. In this stage, two Booster batches are slip stacked for antiproton production and nine Booster batches are slip stacked in the Main Injector for NuMI. Because of the collider batch and the abort space, only 5/7 of the Main Injector is available for slip stacking for NuMI. This limits the number of batches that can be slip stacked for NuMI to nine batches.

Because the Main Injector must be held at 8 GeV while the eleven batches are slip-stacked, the minimum Main Injector cycle time is 2.2 seconds. During this stage, the collider has transitioned away from building large stacks in the Accumulator by off-loading surplus antiprotons to the Recycler at regular intervals. With smaller stacks in the Accumulator, antiproton production can handle a Main Injector cycle time of 2.2 seconds. With nine batches accelerated every 2.2 seconds, the beam power at 120 GeV reaches 430 kW.

To handle the demand for more protons, the beam loss per Booster acceleration cycle must be reduced by a factor of almost two. This is accomplished by a combination of removing known aperture restrictions, re-aligning the magnets, and reducing the closed orbit distortion with a ramped corrector system. The reduction in misalignment and closed orbit distortion has to be over 60% to achieve the target acceleration efficiency.

2.3 Stage 2

When the collider run concludes sometime after the end of fiscal year 2009, there will be no need to produce antiprotons at Fermilab. The Recycler can be easily converted into a proton accumulator by directly connecting the Booster to the Recycler. Since the

Main Injector and the Recycler share the same tunnel, this would be done by modifying the transfer line that presently connects the Booster to the Main Injector so that the line connects directly from the Booster to the Recycler.

The main advantage to using the Recycler as a proton accumulator is a significant decrease in Main Injector cycle time. In Stage 1, the Main injector must be held at 8 GeV for 0.7 seconds while the Main Injector is loaded with the eleven Booster batches for slip stacking. In Stage 2, slip-stacking can be done in the Recycler while the Main Injector is ramping and delivering protons to the 120 GeV neutrino production target. The Recycler can transfer its proton load to the Main Injector in a single turn which results in a reduction in cycle time from 2.2 seconds in Stage 1 to 1.5 seconds in Stage 2. Because the Recycler is the same circumference as the Main Injector and there is no antiproton production during Stage 2, the number of batches destined for the neutrino target increases from nine to twelve. The net increase proton flux from Stage 1 to Stage 2 is over 65%.

As shown in Table 2-1, the proton flux through the Booster is the same for Stage 1 and Stage 2 so no new upgrades are needed for the Booster in Stage 2. In addition to the modification of the Booster transfer line, the Recycler would require an RF system that has the same frequency as the Booster RF system (53 MHz). Because the Recycler 53 MHz RF system would only be used for slip stacking which only requires low RF voltages, only two 53 MHz RF cavities need to be installed in the Recycler. These cavities can be reused Tevatron cavities. In addition there would be modifications to the Recycler instrumentation such as the damper systems and the beam position system to see the 53 MHz beam. Because the Recycler was designed to handle ultra-dense antiproton beams, it has much lower impedance than the Main Injector and should be able to handle as much beam intensity as the Main Injector. The beam power at 120 GeV in Stage 2 would reach 720 kW.

2.4 Stage 3

The amount of batches that can be slip stacked in the Recycler is limited by the longitudinal emittance dilution and beam loss during slip-stacking. Barrier bucket stacking would have less longitudinal emittance dilution than slip stacking. However, barrier buckets require wideband RF cavities and power amplifiers which can provide a limited amount of voltage. Obtaining sufficient barrier height for the current Booster momentum spread might be difficult. The low RF voltage also constrains the speed of the stacking process because of the resulting slow synchrotron frequency. Because slip stacking and barrier bucket stacking require manipulating intense beams in a mostly empty ring, beam loading issues are important.

In addition, because Booster batches must be loaded sequentially in the Recycler on the same orbit for either slip-stacking or barrier bucket stacking, the Booster must align to the Recycler at extraction. For this alignment, the Booster must cog in relation to the beam already present in the Recycler. Booster cogging requires that the notch in the beam for the extraction kicker be created in the Booster. This creation of this notch causes a significant amount of beam loss and places additional constraints on the radial position of the beam during acceleration which can adversely impact the effective aperture.

As discussed in Section 1.2.1, momentum stacking results in much less longitudinal emittance dilution than slip stacking. With the present Booster longitudinal emittance, at least four Booster batches could be momentum stacked in the Accumulator with a resulting longitudinal emittance smaller than the Main Injector longitudinal acceptance. Once four batches have been stacked in the Accumulator, the beam is transferred to the Recycler. Since the Recycler has seven times the circumference of the Accumulator, the Recycler has room for six transfers from the Accumulator.

To transfer directly from the Booster to the Accumulator, a 240 meter long transfer line would have to be built. Also to transfer from the Accumulator to the Recycler, a 100 meter long transfer line would also have to be installed. It might be possible to build a large portion of these transfer lines while the complex is running Stage 2. Many of the magnets and power supplies that are currently used for the present 400 meter long antiproton source injection and extraction lines could be re-used.

In Stage 3 the Booster would be running at almost double the repetition rate than in Stage 2. However, the intensity per batch is significantly lower in Stage 3 which relaxes the aperture requirements substantially. In addition, a large source of Booster loss can be removed because injection into the Accumulator for momentum stacking does not require the Booster to align at extraction (cog) to the Accumulator. The elimination of cogging permits the creation of the beam gap used to clear the extraction septum to be done in the Linac at low energy. The result is no additional Booster upgrades are needed in Stage 3. However, more design margin in aperture and beam loss could be provided if the DC dogleg four bump in the Booster extraction system is replaced with a pulsed three bump. With Booster batches extracted at 15 Hz rate with an intensity of 4.0×10^{12} protons per batch, a 1.1 megawatt beam in the Main Injector can be achieved for Stage 3.

2.5 Stage 4

Momentum stacking in the Accumulator followed by box-car stacking in the Recycler requires Booster batches to be accelerated at a 15 Hz rate. Stage 1 of the present Proton Plan addresses the power systems needed to operate at 15 Hz rate. However, beam loss in the Booster and the resulting tunnel activation will be the ultimate limit on the Booster throughput. To go significantly beyond 1.1 megawatts would require an aperture upgrade to the Booster. It would be difficult and fairly disruptive to the present program to upgrade the present Booster aperture.

If driven by the physics needs, an alternative would be to build a new booster to go beyond 1.1 megawatts. A large amount of work carried out for the design of the synchrotron option of the Proton Driver[3] can be directly applied here. That design study has the extraction intensity of the booster synchrotron at 25×10^{12} protons/batch which, using momentum stacking in the Accumulator, would yield a Main Injector beam of 6.25 megawatts. However, there would be difficult RF issues in the Main Injector for a 6.25 megawatt beam. A more reasonable goal would be a design intensity of 8×10^{12} protons/batch which would yield a Main Injector beam of 2.2 megawatts. Because a batch intensity of 6.5×10^{12} protons has already been obtained with the present Booster, the main issue for this beam intensity would be aperture.

The cost of the new booster can be substantially reduced if the design takes advantage of existing infrastructure and places the new booster in the Antiproton Source tunnel in the current location of the Debuncher. The cost savings are significant because the tunnel, power, utilities, service buildings, and controls infrastructure would be re-used. Also, an intensity of 8×10^{12} protons/batch would require significantly smaller aperture magnets than the design presented in Proton Driver design report. A reasonable estimate for the cost of the new Booster would be less than 100 million dollars.

3 Booster Requirements

3.1 Intensity Limitations

The available beam power is limited by the beam lost in the tunnel. The Booster is operated by keeping the average beam power lost in the tunnel constant. The beam power lost in the tunnel is equal to the energy lost per pulse times the repetition rate.

$$P_L = J_L R \qquad (3\text{-}1)$$

where J_L is the Joules lost per pulse and R is the average repetition rate. As shown in Figure 3-1, the Booster ran at P_L=440W for the month of March 2005.

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Summary for Event 10
From 01-MAR-2005 00:00:00
  to 01-APR-2005 00:00:00

Percentage up time: 88.1
Total Events:     13605200
Total Protons:    4.32E+19
Average Events/second:        5.46
Average protons/Event:        3.35E+12
Average protons/hour:         6.58E+16
Maximum protons/hour:         8.33E+16   03/27/05
(protons out)/(protons in):   .828
(Joules lost)/(1e12 prot):    23.7
```

Figure 3-1 Booster Performance for the month of March 2005

For simplicity the beam loss can be divided into two categories, beam loss due to creating the beam gap (notch) for extraction and beam lost transversely during acceleration.

$$J_L = E_n \Delta N_n + E_A \Delta N_A \qquad (3\text{-}2)$$

where ΔN_n is the amount of beam lost during notching, ΔN_A is the beam loss during acceleration, E_n is kinetic energy when the notch is created, and E_A is the weighted average kinetic energy at which the beam is lost during the acceleration cycle. The energy E_A is a function of the beam loss versus time and is about 900 MeV for present operations (See Figure 3-2)

The total efficiency of the Booster is:

$$\frac{N_{ext}}{N_{inj}} = \left(1 - f_n - f_A\right) \qquad (3\text{-}3)$$

where f_n is the ratio of the amount of beam loss during notching to the injection intensity and f_A is the ratio of the amount of beam loss during acceleration to the injection intensity. For a given notching fraction, the fraction of beam loss during acceleration that can be tolerated is:

$$f_A = \frac{P_L - \left(N_{ext} E_n R + P_L\right) f_n}{N_{ext} E_A R + P_L} \qquad (3\text{-}4)$$

Assuming a guassian profile as a simple approximation, the amount of beam in the halo that is outside the aperture is:

$$f_h = e^{-3\frac{A}{\varepsilon_{95}}} \qquad (3\text{-}5)$$

where A is the aperture and ε_{95} is the 95% emittance. The amount of beam that is permitted to be in the halo is:

$$f_h = \frac{\Delta N_A}{2\left(N_{ext} + \Delta N_A\right)} = \frac{f_A}{2\left(1 - f_n\right)} \qquad (3\text{-}6)$$

where the factor of 2 comes from the halo in both planes. The aperture required is:

$$A = \frac{S_f \varepsilon_{95}}{3} \ln\left(\frac{2\left(1 - f_n\right)}{f_A}\right) \qquad (3\text{-}7)$$

where an extra "safety" factor, S_f, was added. This safety factor would have to be about 1.65 to satisfy the requirements in the Proton Driver design report.

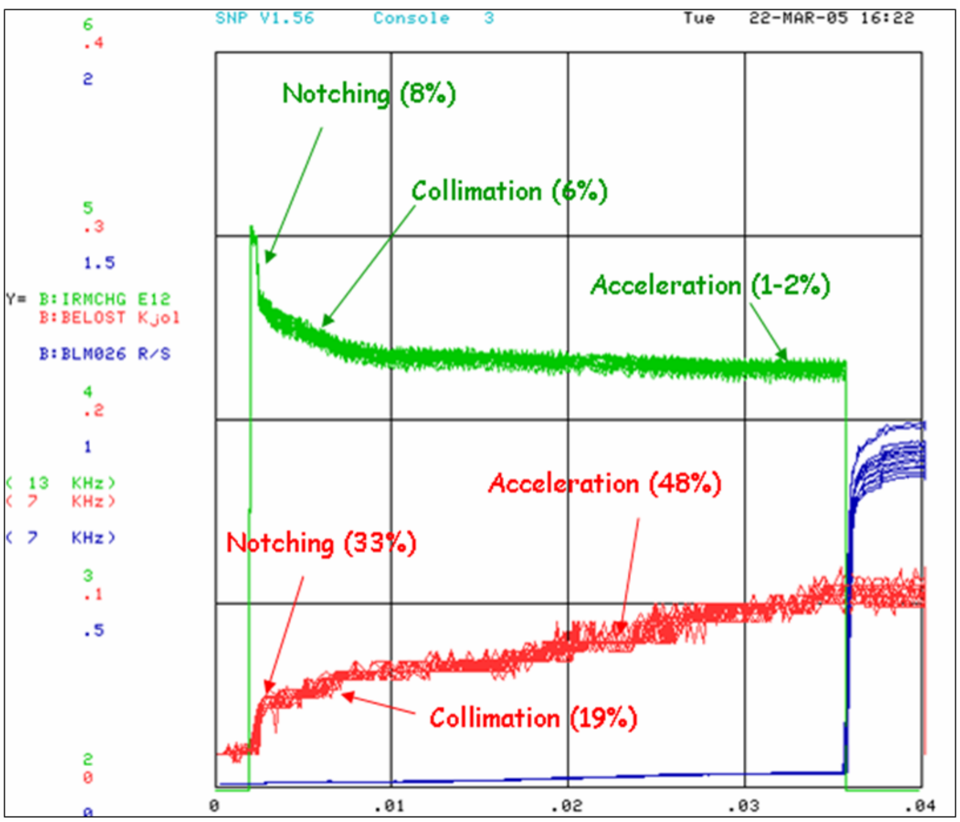

Figure 3-2 Typical Booster Intensity Profile

As a basis for comparing different Booster designs, the minimum beam emittance at injection is determined by the incoherent space charge tune shift:

$$\varepsilon_n = B\frac{3r_o}{2\pi}\frac{N_{inj}}{\beta\gamma^2\Delta\nu} \tag{3-8}$$

where N_{inj} is the injection intensity, ε_n is the normalized emittance at injection, β is the ratio of the velocity of the beam to the velocity of light, γ is the ratio of the beam energy to the rest energy, $\Delta\nu$ is the incoherent space charge tune shift, B is the bunching factor and r_o is the classical radius of the proton ($1.53\text{x}10^{-18}$meters).

In the Proton Driver design report, the half aperture of the magnets must exceed:

$$\Delta x = \sqrt{\frac{A_n}{\beta\gamma}\beta_{max}} + \frac{\Delta p}{p}D_{max} + \Delta x_{align} + c.o.d \tag{3-9}$$

where A_n it the normalized acceptance, β_{max} is the maximum lattice beta function, D_{max} is the maximum lattice dispersion function, p is the beam momentum, Δp is the momentum spread, Δx_{align} is a measure of the magnet misalignment, and c.o.d. is the closed orbit distortion.

3.2 Booster Aperture Requirements

The intensity and repetition requirements for each stage are shown in the first two rows of Table 3-1. It is assumed that the amount of beam loss that can be tolerated in the tunnel will remain unchanged. Because slip stacking is used in Stages 1 and 2, the Booster must align to the downstream machine. Since aligning the Booster will require cogging in the Booster, the notch must be created in the Booster and the loss due to creating this gap must be taken into account. As shown in Figure 3-2, this beam loss is rather severe. There are planned improvements to the Booster cogging system in Stage 1 that will permit the creation of a shorter notch. For momentum stacking, the Accumulator will align to the Booster because there is no beam on the injection orbit of the Accumulator. With no cogging required in the Booster for momentum stacking, the notch will be created at the low energy end of the Linac in Stages 3 and 4. The allowed space charge tune shift for all the designs was taken from the Proton Driver design report.

Parameter	Present	Stage 1-2	Stage 3	Stage 4	PD2	
Extraction Intensity	3.35	4.7	4	8	25	$\text{x}10^{12}$
Rep. Rate	5.46	8	15	15	15	Hz
Average Beam Power Lost	443	443	443	443	443	Watts
Notch Bunches	7	4	0	0	0	
Notch Energy	450	450	450	450	650	MeV
Accelelerion Loss Energy	900	900	900	900	900	MeV
Injection Energy	400	400	400	400	600	MeV
Allowed Tune Shift	0.47	0.47	0.47	0.47	0.47	
Bunching Factor	2	2	2	2	2	

Table 3-1 Booster Intensity Requirements

The required acceleration efficiencies for the desired beam intensities are shown in Table 3-2. Because of the lower intensity per pulse and no notch loss in Stage 3, the transverse acceptance requirement drops by 20% from Stage 2 to Stage 3.

Parameter	Present	Stage 1-2	Stage 3	Stage 4	PD2	
Acceleration loss	9.6	5.0	4.9	2.5	0.8	%
Efficiency	82.0	90.2	95.1	97.5	99.2	%
Injection Intensity	4.1	5.2	4.2	8.2	25.2	$x10^{12}$
Norm. Emittance at Inj	8.7	11.2	9.0	17.6	36.8	π-mm-mrad
Norm Acceptance at Inj	14.0	22.0	18.1	41.7	109.6	π-mm-mrad

Table 3-2 Minimum acceleration efficiencies and transverse acceptances

Once the lattice functions are known and the momentum acceptance and the closed orbit tolerance is specified, then the minimum accelerator aperture can be determined. An aperture safety factor of 1.65 used in Eqn. 3-7 was used for all of the designs. The maximum lattice functions for all the stages are shown in Table 3-3. The key upgrade of Stage 1 of the Proton Plan is to reduce magnet misalignment and the closed orbit distortion by 62%. Because, the alignment and the closed orbit tolerance is relaxed in Stage 3, the efficiencies required for Stage 3 are more conservative than for Stage 1 and 2.

Parameter	Present	Stage 1-2	Stage 3	Stage 4	PD2	
F magnet β_x	33	33	33	15	15	m
F magnet β_y	14	14	14	20	20	m
F magnet D_x	3	3	3	2.5	2.5	m
D magnet β_x	14	14	14	15	15	m
D magnet β_y	22	22	22	20	20	m
D magnet D_x	2.5	2.5	2.5	2.5	2.5	m
Momentum Acceptance	0.4	0.4	0.4	1.2	2.4	%
Misalignment & c.o.d.	13	5	10	20	20	mm

Table 3-3 Booster lattice functions and closed orbit tolerances

The vertical aperture in the present Booster is 1.64 inches and 2.25 inches for the F magnets and D magnets, respectively. The horizontal good field aperture is 4.3 inches and 3 inches. The RF cavities in the Booster are located between two D magnets where the horizontal beta function is at a minimum and the vertical beta function is a maximum. The RF cavity aperture is 2.25 inches. With the intensities required in Table 3-1, these apertures are larger than the minimum required apertures shown in Table 3-4.

Parameter	Present	Stage 1-2	Stage 3	Stage 4	PD2	
F Aperture Width	2.7	2.8	2.8	3.9	6.0	in
F Aperture Height	1.6	1.6	1.6	3.0	4.0	in
D Aperture Width	2.0	2.0	2.0	3.9	6.0	in
D Aperture Height	1.9	1.9	2.0	3.0	4.0	in

Table 3-4 Minimum Booster apertures

4 Momentum Stacking in the Accumulator

4.1 Overview

The key features of RF momentum stacking are a large momentum aperture and injection system located at high dispersion. Because the same features are required for stochastic momentum stacking of antiprotons, RF momentum stacking in the Accumulator would be possible with only minor modifications to the Accumulator.

During momentum stacking, a Booster batch is placed on the injection orbit of the Accumulator and accelerated towards the high energy aperture as shown in Figure 4-1. Another Booster batch is injected onto the injection orbit and accelerated towards the high energy aperture and deposited adjacent to the previous batch. The limit to how many Booster batches can be stacked is not the Accumulator aperture but the momentum aperture of the Main Injector at the transition energy. With present Booster performance, the Main Injector momentum aperture can comfortably handle over four Booster batches. This large number of batches can be combined using momentum stacking because momentum stacking has very little longitudinal emittance dilution.

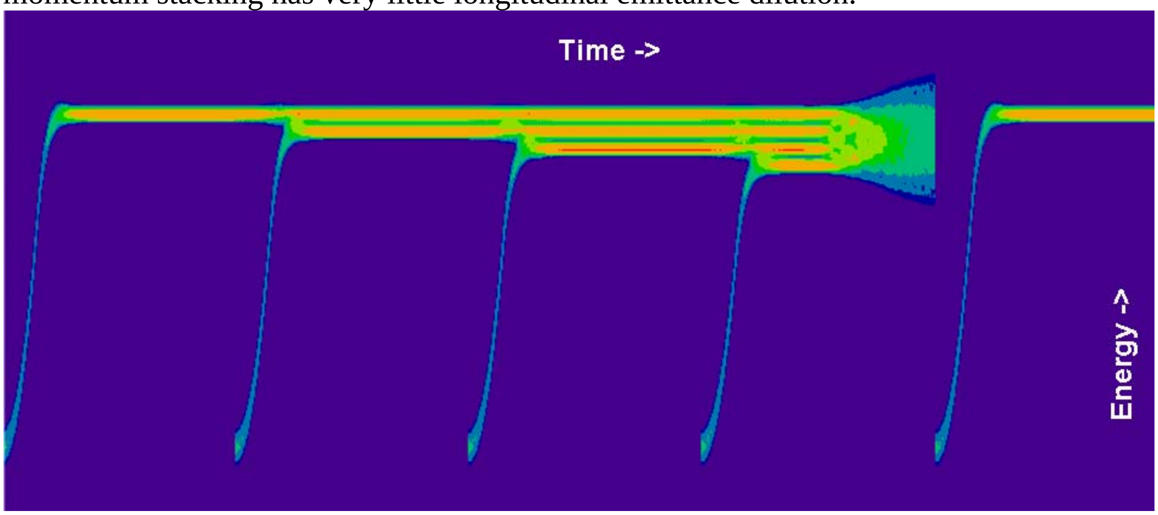

Figure 4-1 Tracking simulation of the energy profile vs time for momentum stacking four Booster batches.

4.2 Injection and Extraction Transfer Lines

To transfer directly from the Booster to the Accumulator, a 240 meter long transfer line would have to be built as shown in Figure 4-2. This transfer line would lie along the same trajectory as the abandoned AP4 line that was used to commission the Antiproton Source in Run I. The new AP4 line would connect directly from the Booster near the Long 3 sector and inject into the present Debuncher at the D30 sector. In Stage 3, the line would operate at 8 GeV. The beam would spend 2/3 of a turn in the Debuncher before transferring into the present Debuncher to Accumulator (D/A) transfer line. The pulsed devices for injecting and extracting into and out of the Debuncher would be replaced with DC magnets.

As a basis for comparison, the civil construction cost estimate for the 250 meter long, 600 MeV transfer line in the Proton Driver design report is 1.8 million dollars. Since the transfer line connecting the antiproton production target to the Debuncher (AP2 line) will no longer be needed, a good fraction of the magnets and power supplies used in the AP2 line could be re-installed in the new AP4 line for Stage 3. In Stage 4, the new AP4 line will operate at 400 MeV. A short section of transfer line (~40 meters) will have to be extended from the present 400 MeV line at Booster Long 1 to the Booster Long 3 sector. In the event that the 8 GeV magnets used in Stage 3 are unsuitable for operating at 400 MeV in Stage 4, the magnet cost in the Proton Driver design report for the 600 MeV transfer line is 1 million dollars.

To transfer from the Accumulator to the Recycler, a 100 meter long transfer line would also have to be built as shown in Figure 4-2. This line connects the existing AP3 and MI8 lines. The connection to the Recycler from MI8 is done for Stage 2. Since this line will only use a small fraction of the existing AP3 line, the magnets and power supplies from the rest of the AP3 line can be re-used in this new transfer line. The civil construction cost for 420 meter long 8 GeV line in the Proton Driver design report is 2.2 million dollars. Comparing the civil construction costs for the two transfer lines, a reasonable estimate for the civil construction of the AP3 line modification would be 1.4 million dollars.

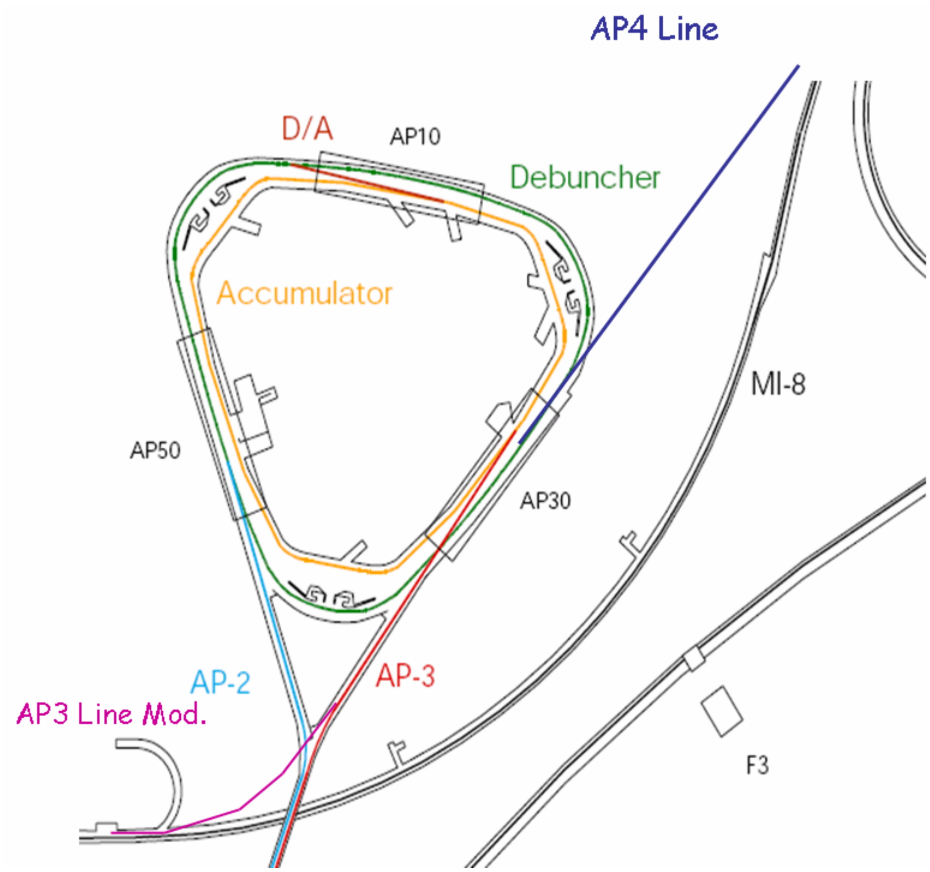

Figure 4-2 Layout of New AP4 line and AP3 line modification

4.3 Momentum Stacking Phase Space

In momentum stacking, a single Booster batch is accepted into the Accumulator, accelerated towards the high energy aperture, and de-bunched in one Booster period. Because the kickers in the Accumulator are located at high dispersion, the injection kick will affect only the injected beam and any beam on the other side of the momentum aperture will remain undisturbed.

At injection into the Accumulator, the RF system must provide enough bucket area to hold the injected beam. Presently, the longitudinal emittance per 53 MHz bunch at extraction from the Booster is about 0.08 eV-Sec for a batch intensity of 4.2×10^{12} protons. A reasonable value for the capture bucket in the Accumulator would be 0.2 eV-Sec. Once the beam is captured in the Accumulator, the bucket is accelerated towards the high energy side of the momentum aperture with a constant bucket area. Because all the RF manipulations must be done before the next batch is injected, the batch should reach the high energy side of the Accumulator in about 10 mS.

When the high energy edge of the bucket reaches the target energy, the bucket area is shrunk while keeping the high energy edge of the bucket fixed at the target energy. This period while the bucket is shrinking with the high energy edge fixed should take an additional 10 mS. When the bucket area has shrunk to the beam area, the bucket stops accelerating and de-bunches. The de-bunching process will take another 10 mS. The whole process requires 30 mS which leaves 37 mS before another batch is injected. The extra 37 mS will be used to recapture the batches for extraction from the Accumulator. The bucket area curve is shown in Figure 4-3 and the frequency curve is shown in Figure 4-4. For simplicity, the de-bunching curve for this example is a linear profile. Better emittance performance might be obtained if a more adiabatic profile is chosen. The voltage needed for the required bucket area and acceleration rate is shown in Figure 4-5. The maximum 53 MHz voltage required for the accelerating 0.2 eV-Sec bucket is 80 kV. The present Accumulator RF system has two cavities that could provide 35 kV of RF each. In comparison, a 0.14 eV-Sec accelerating bucket requires 60 kV. A third RF cavity is probably necessary.

Figure 4-6 shows a tracking simulation of the resulting longitudinal phase space of four Booster batches that were momentum stacked using the RF curves shown in Figure 4-3 through Figure 4-5. Since the harmonic number of the Accumulator is 84, each picture in Figure 4-6 shows four buckets or 1/21 of the circumference of the Accumulator. The longitudinal emittance of the Booster batch used in these simulations is 0.08 eV-sec per 53 MHz bucket. The total longitudinal emittance for the coasting beam at the end of the process is 84 x 0.38 eV-Sec. This corresponds to an emittance dilution of 19%. A simulation using an initial emittance of 0.10 eV-sec was performed and the resulting coasting beam emittance was 84 x 0.47 eV-Sec which corresponds to a dilution of 18%. For simulation using an initial emittance of 0.12 eV-sec, only three batches were momentum stacked to give a coasting beam emittance of 84 x 0.43 eV-Sec. Three batch momentum stacking would require a faster Main Injector cycle time of 1.2 seconds to deliver the same 120 GeV beam power as four batch stacking.

There has been significant work on decreasing the Booster longitudinal emittance for slip-stacking. Without using the gamma-t jump in Booster, the longitudinal emittance per 53 MHz bunch at extraction from the Booster is about 0.08 eV-Sec for a batch intensity of 4.2×10^{12} protons. Most of the longitudinal emittance growth occurs at transition in the Booster. The Booster gamma-t jump is not currently used because it interferes with cogging. Currently an RF step at transition is under consideration to decrease the longitudinal emittance. Since cogging in the Booster is not required in Stage

3, another reduction in longitudinal emittance might be possible if the Booster gamma-t jump is re-commissioned.

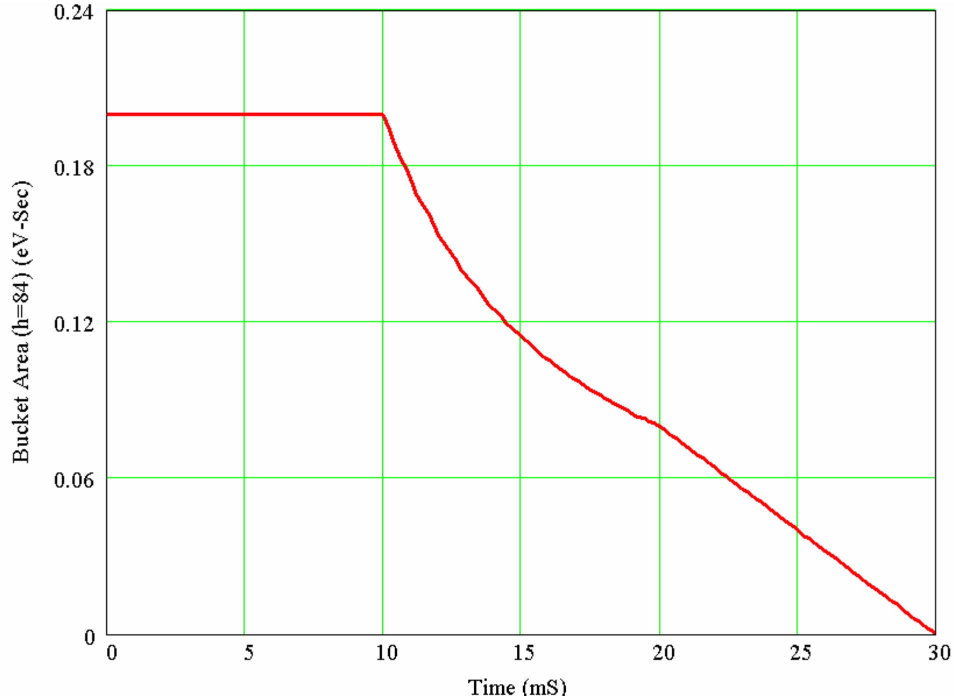

Figure 4-3 53 MHz Bucket Area during Momentum Stacking

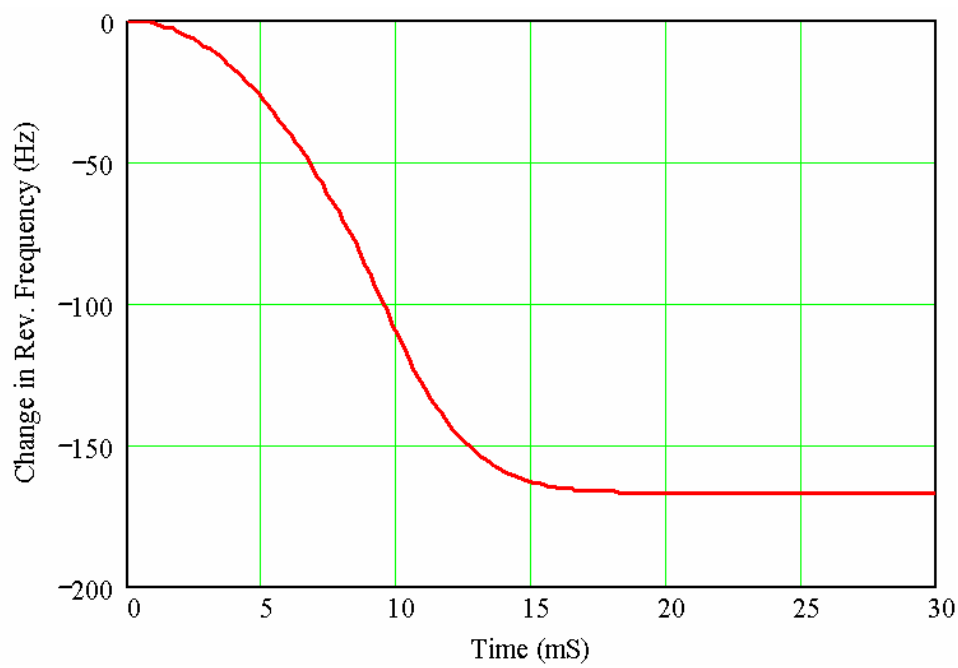

Figure 4-4 53 MHz Relative revolution frequency during momentum stacking. The first 10 mS of the curve is a second order polynomial and the second 10 mS of the curve is a fourth order polynomial.

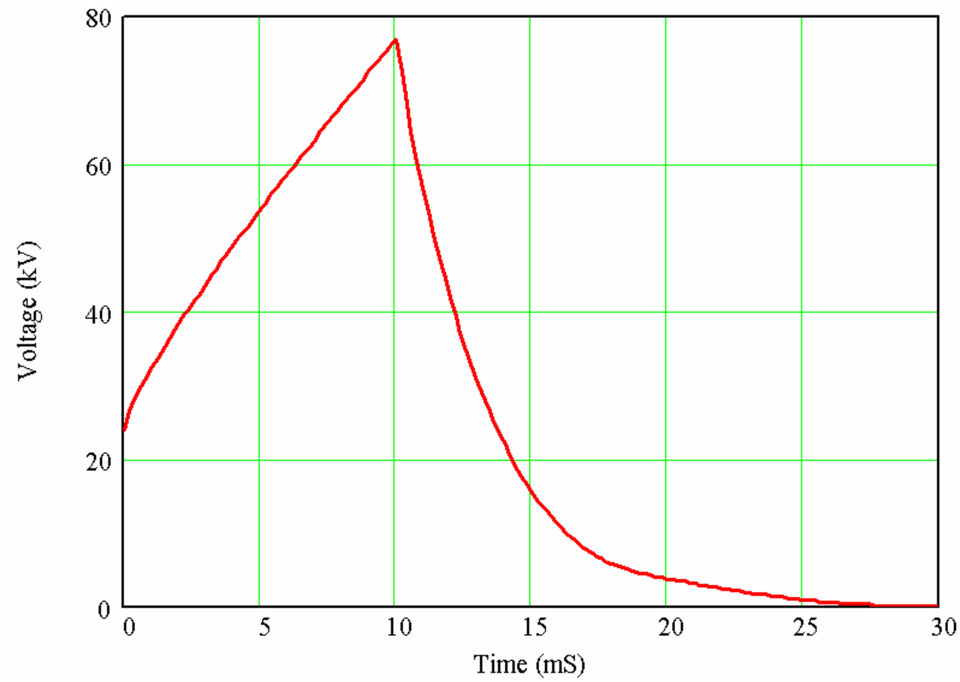

Figure 4-5 53 MHz RF Voltage during momentum stacking

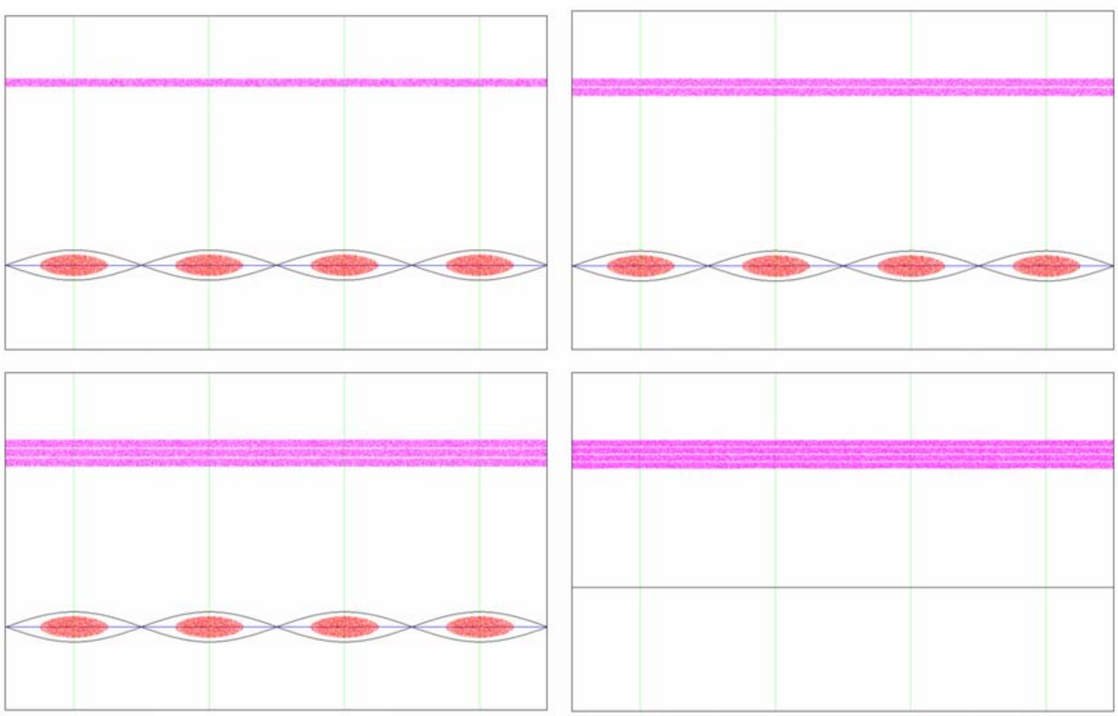

Figure 4-6 Tracking simulations of momentum stacking. The red particles are freshly injected beam from the Booster. The magenta particles is coasting beam that has been momentum stacked

4.4 Extraction Process

The low emittance dilution of the momentum stacking process is a result of de-bunching the batches into coasting beam. Because of kicker rise time, a gap must be placed in the coasting beam so that no beam is lost while the extraction trajectory is swept across the face of the extraction magnet. With the large amount of proton flux, small transfer inefficiencies can result in a substantial amount of tunnel activation. With 4.0×10^{12} 8 GeV protons per batch transferring at a 15 Hz rate, a beam loss of 0.7% is equivalent to a beam power of 500W. The beam gap could be formed with a barrier bucket. A 10 kV barrier that is 120 nS wide would be required to form a barrier in the coasting beam distribution shown in Figure 4-6. The wideband RF power supply to generate a 10 kV barrier would be substantial. More importantly, the synchrotron frequency for a 10 kV barrier is slower than the Booster repetition rate. Forming a barrier faster than the Booster repetition rate would result in substantial emittance dilution.

Another choice for forming this gap would be to bunch the beam with a sinusoidal RF. For a 53 MHz bunch structure, the kicker rise time would have to be faster than 10 nS which would be extremely difficult to achieve at 8 GeV. Larger gaps can be made with lower frequency RF. Because the bunching process should not result in significant emittance dilution, the synchrotron frequency must be much higher than the Booster repetition rate. For example, the synchrotron frequency needed to bunch the beam at 2.5 MHz (h=4) is only 60 Hz while the synchrotron frequency for the beam bunched at 7.5 MHz (h=12) is over 180 Hz. The gap that can be created in the beam with 7.5 MHz RF bucket that is 70% full is over of 45 nS. The present Accumulator injection and extraction kickers would have to be re-built to have a rise time smaller than this gap.

Because the momentum stacking curves shown in Figure 4-3 through Figure 4-5 are 30 mS long, the extraction curves can span up to 37 mS before the next Booster batch is injected into the Accumulator. For an h=12 RF system (7.5 MHz), the bucket area needed to capture the coasting beam distribution is 2.75 eV-Sec. As shown in Figure 4-8 through Figure 4-9, the RF voltage is ramped up to 32 kV to provide a 4.2 eV-Sec bucket at extraction. As shown in Figure 4-7, a 4.2 eV-Sec bucket will leave a gap between bunches of about 45 nS. For this example, the bucket area is linear time ramp which will result in a small amount of longitudinal emittance growth. The h=12 emittance that contains 100% of the particles before extraction is 2.75 eV-sec. The 95% emittance after extraction is 2.5 eV-Sec.

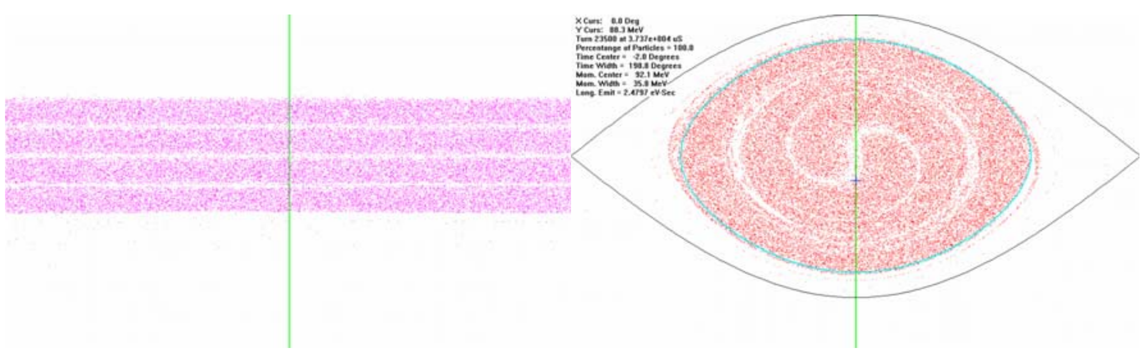

Figure 4-7 7.5 MHz phase space distribution before and after the extraction process. The longitudinal emittance for 100% of the particles is 2.75 eV-sec before extraction. The cyan trace is the trajectory that contains 95% of the particles at extraction (~2.5 eV-Sec.)

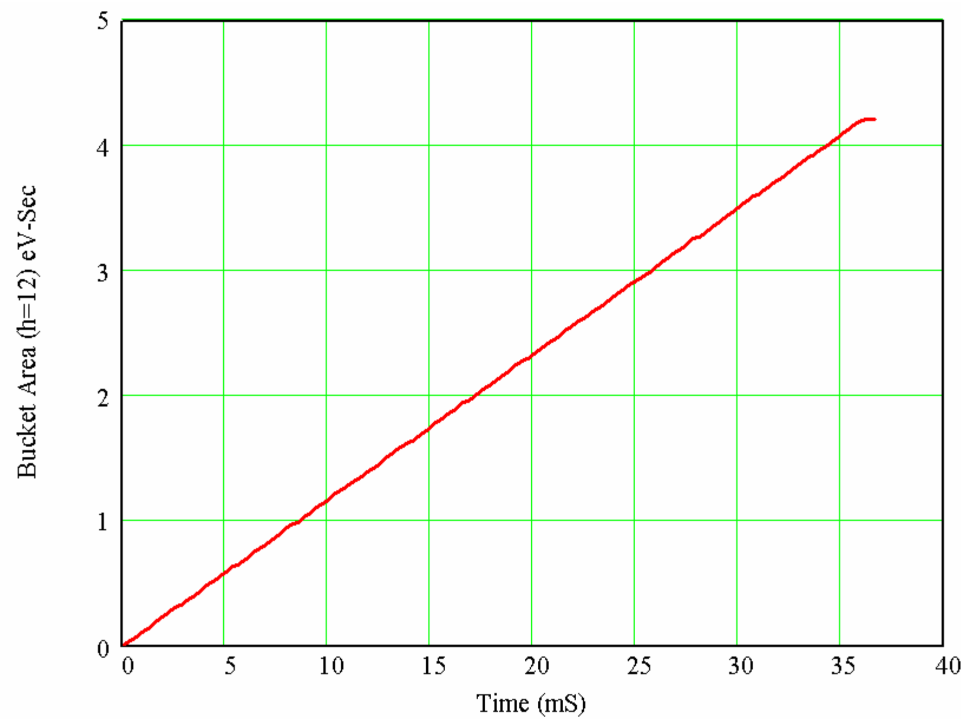

Figure 4-8 Bucket area profile for 7.5 MHz (h=12) extraction from the Accumulator

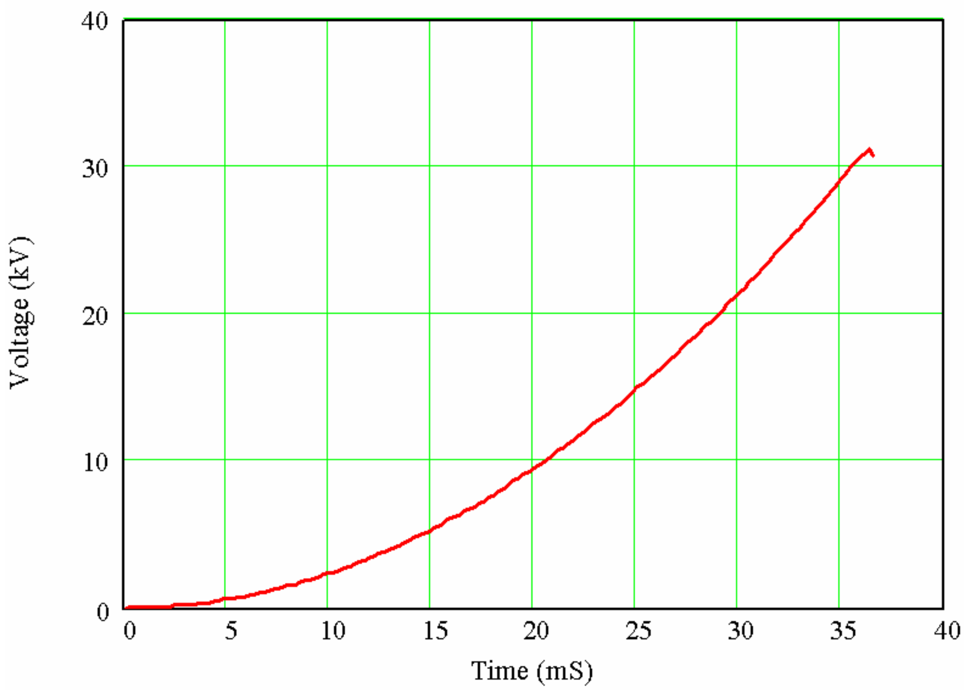

Figure 4-9 RF voltage profile for 7.5 MHz (h=12) extraction from the Accumulator

4.5 RF Manipulations in the Recycler

The Recycler will also require a 7.5 MHz (h=84) RF system for synchronous bucket to bucket transfers from the Accumulator. To match to a 4.2 eV-Sec bucket, the Recycler RF system will require 80 kV at 7.5 MHz. Because the magnets and the frequency of the 7.5 MHz RF systems in both the Accumulator and Recycler do not ramp, a phase alignment and frequency jump system instead of a phase lock system for synchronizing transfers should suffice. Using a phase alignment system would permit the entire 37 mS period left for extracting the beam from the Accumulator to be used for bunching the beam.

Once the 7.5 MHz bunches have been transferred to the Recycler, the beam must be debunched out of the 7.5 MHz buckets and recaptured into 53 MHz buckets for transfers to the Main Injector. There will be 266 mS for this process while the Accumulator is momentum stacking another four Booster batches. Because the synchrotron period for the 7.5 MHz bunches is approximately twice as long in the Recycler as it is in the Accumulator, the 7.5 MHz de-bunching process in the Recycler should take over 75 mS.

About 500 kV of 53 MHz RF (h=588) is needed in the Recycler to provide 0.6 eV-Sec of bucket area which should be enough to re-capture and extract the 0.4 eV-Sec longitudinal emittance of the 53 MHz bunches. Because the current Tevatron RF system can provide over 2.0 MV of 53 MHz RF with eight cavities and the Recycler 53 MHz frequency does not need to ramp, three of the Tevatron cavities along with the power amplifiers could be installed into the Recycler to provide the necessary RF voltage. Because the fill time of the Tevatron cavities is about 0.2 mS. and the synchrotron frequency for 500kV of 53 MHz RF in the Recycler is 550 Hz., the remaining 190 mS should more than adequate to re-bunch the beam at 53 MHz in the Recycler.

4.6 Cost Estimate

Description	Cost
Linac Notching	100
Booster Extraction Upgrade	1,000
AP4 Line Civil	1,800
AP4 Tie In & Installation	500
AP3 Modification Civil	1,400
AP3 Tie In & Installation	500
Accumulator Shielding	3,000
Accumulator Kickers	1,000
Accumulator 53 MHz RF	400
Accumulator 7.5 MHz RF	400
Accumulator Instrumentation	200
Recycler 7.5 MHz RF	1,000
Recycler 53 MHz Installation	300
Recycler Instrumentation	200
Total	11,800

Table 4-1 Cost Estimate for Stage 3 in k$

Table 4-1 shows a cost estimate of the projects needed to complete Stage 3. It does not include the costs for Stages 1-2.

5 Wide Aperture Booster

5.1 Lattice

If driven by the physics needs to go beyond 1.1 megawatts, a new booster is required. A large amount of work carried out for the design of the synchrotron option of the Proton Driver can be directly applied. That design study has the extraction intensity of the booster synchrotron at 25×10^{12} protons/batch. However, using the Accumulator as a proton accumulator reduces the peak intensity requirement in the booster. The lower peak intensity has a smaller space charge tune shift and relaxed requirements on acceleration efficiency which results in a smaller required aperture for the new booster. A more reasonable goal of 8×10^{12} protons/batch for the booster intensity yields a Main Injector beam of 2.2 megawatts. As shown in Table 3-4, this intensity would require significantly smaller aperture magnets than the design presented in the Proton Driver design report.

The cost of the new booster can be substantially reduced if the design takes advantage of existing infrastructure and places the new booster in the Antiproton Source tunnel in the current location of the Debuncher. The cost savings are significant because the tunnel, power, utilities, service buildings, and controls infrastructure would be re-used.

An initial design of a lattice with a triangular shape to fit into the Debuncher footprint is shown in Figure 5-1. The lattice is a doublet lattice with 90 degrees per cell. There are 3 cells per module with a missing dipole in the middle cell. There are four modules per arc and the phase advance per arc is 6π. The lattice has low beta functions (16 meters) and dispersion (2.4 meters) as shown in Figure 5-2. The lattice has good optical properties with a relatively large dynamic aperture and a weak dependence of lattice functions on amplitude and $\Delta p/p$. There are three zero dispersion straight sections with a total available free space of over 180 meters for injection, extraction, and the RF cavities. The magnet requirements are simple; one type of dipole and quadrupole with a peak bend field of 1.5 Tesla and a peak gradient of 10.3 Tesla/meter. Because the lattice has a γ_t of 18.1, the beam will not have to go through transition. The lack of transition crossing should provide a much lower longitudinal emittance than is currently achieved in the present Booster.

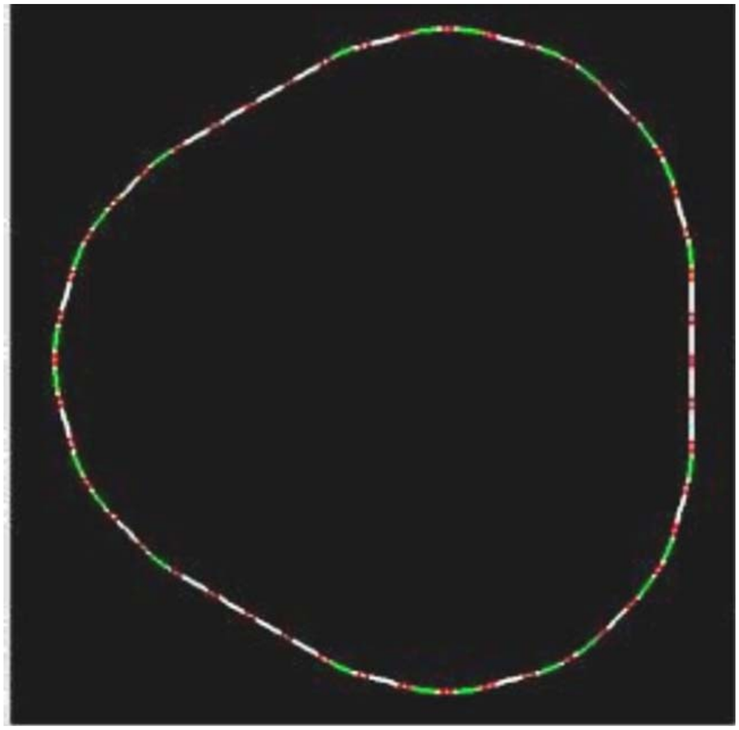

Figure 5-1 Layout of new booster

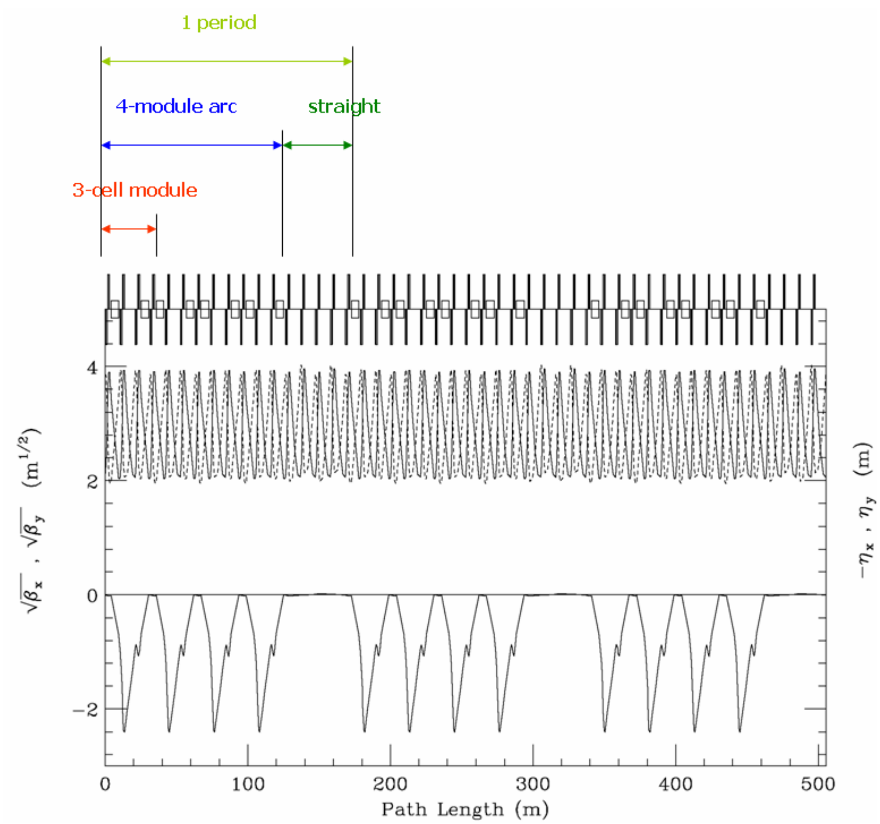

Figure 5-2 Lattice unctions of the new booster

5.2 Cost Scaling

A detail cost estimate for the new booster has not been done. However, an initial estimate of the cost for the new booster can be made by scaling the cost of the synchrotron option in the Proton Driver design report. Table 5-1 gives a breakdown of the cost for the synchrotron option in the Proton Driver design report which totals over 136 million dollars. Table 5-2 shows the cost estimate for the Stage 4 booster which totals over 75 million dollars.

The Proton Driver design report planned on spending 17.5 million dollars to upgrade the Linac to 600 MeV which is not needed for Stage 4. Also, since the new booster uses the existing Debuncher tunnel and the transfer line costs are included in Stage 3, the Stage 4 booster saves about 34 million dollars in civil construction. The 3 million dollars that is allocated in civil construction is for increasing the shielding in the Debuncher tunnel. This is in addition to the 3 million dollars allocated in Stage 3 to shield the Accumulator.

Because the magnet aperture for the Stage 4 booster is significantly smaller, about 20 million dollars can be saved on magnets and power supplies. A credit of about 6.4 million dollars can be taken for reusing the existing controls and utilities. The Proton Driver planned on retro-fitting aperture of the present Booster RF cavities and using them in the synchrotron. Because of the activation of the cavities, it would be impractical to re-machine the RF cavities. The cost estimate in Stage 4 assumes that the entire cavity system will be replaced for a cost of about 25 million dollars. This cost could be reduced significantly if the power supplies and amplifiers for the present Booster are reused.

Another way to examine the cost scaling is to compare the cost of the Brookhaven AGS Booster as shown in Table 5-3. The AGS Booster was built in 1991 for a cost of 32 million dollars. If the cost is scaled for 14 years of inflation at 4 percent per year, the cost today would be 55 million dollars. The AGS Booster is about half the size of the Stage 4 booster. If the AGS Booster cost is scaled as the total length of the magnets, the cost would scale to 122 million dollars. Adding 37 million dollars in civil construction costs to the Stage 4 booster would amount to 112 million dollars.

WBS	Description	Level 3	Level 2	Level 1
1	Technical Systems			98,986
1.1	8 GeV Synchrotron		78,997	
1.1.1	Magnets	27,329		
1.1.2	Power supplies	25,968		
1.1.3	RF	5,115		
1.1.4	Vacuum	6,061		
1.1.5	Collimators	325		
1.1.6	Injection system	938		
1.1.7	Extraction system	2,189		
1.1.8	Instrumentation	2,393		
1.1.9	Controls	2,468		
1.1.10	Utilities	4,931		
1.1.11	Installation	1,280		
1.2	Linac Improvements and Upgrade		17,500	
1.2.1	Front end and RFQ	3,000		
1.2.2	New drift tube Tank #1	1,000		
1.2.3	Transfer line to new CCL	1,800		
1.2.4	New CCL modules and klystrons	11,100		
1.2.5	Controls and diagnostics	600		
1.3	600 MeV Transport Line		900	
1.3.1	Magnets	720		
1.3.2	Power supplies	180		
1.4	8 GeV Transport Line		1,589	
1.4.1	Magnets	1,271		
1.4.2	Power supplies	318		
2	Civil Construction			37,593
2.1	8 GeV Synchrotron		17,500	
2.1.1	Enclosure	7,000		
2.1.2	Service buildings	7,000		
2.1.3	Utility support building	3,500		
2.2	Linac extension		2,500	
2.3	600 MeV Transport Line		1,800	
2.4	8 GeV Transport Line		2,200	
2.5	Site work		4,800	
2.6	Subcontractors OH&P		5,760	
2.8	Environmental controls and permits		3,033	
	TOTAL ($k)			136,579

Table 5-1 Cost estimate for the synchrotron option of the Proton Driver

WBS	Description	Level 3	Level 2	Level 1
1	Technical Systems			72,317
1.1	8 GeV Synchrotron		71,597	
1.1.1	Magnets	17,329		
1.1.2	Power supplies	15,968		
1.1.3	RF	25,115		
1.1.4	Vacuum	5,061		
1.1.5	Collimators	325		
1.1.6	Injection system	938		
1.1.7	Extraction system	2,189		
1.1.8	Instrumentation	2,393		
1.1.9	Controls	468		
1.1.10	Utilities	531		
1.1.11	Installation	1,280		
1.2	Linac Improvements and Upgrade		0	
1.2.1	Front end and RFQ	0		
1.2.2	New drift tube Tank #1	0		
1.2.3	Transfer line to new CCL	0		
1.2.4	New CCL modules and klystrons	0		
1.2.5	Controls and diagnostics	0		
1.3	600 MeV Transport Line		720	
1.3.1	Magnets	720		
1.3.2	Power supplies	0		
1.4	8 GeV Transport Line		0	
1.4.1	Magnets	0		
1.4.2	Power supplies	0		
2	Civil Construction			3,000
2.1	8 GeV Synchrotron		3,000	
2.1.1	Enclosure	3,000		
2.1.2	Service buildings	0		
2.1.3	Utility support building	0		
2.2	Linac extension		0	
2.3	600 MeV Transport Line		0	
2.4	8 GeV Transport Line		0	
2.5	Site work		0	
2.6	Subcontractors OH&P		0	
2.8	Environmental controls and permits		0	
	TOTAL ($k)			75,317

Table 5-2 Cost estimate of the Stage 4 booster

	Stage 4 booster	AGS Booster
Circumference (m)	505	201
Injection (MeV)	400	200
Extraction (GeV)	8	1.5
Rep rate (Hz)	15	7.5
Total dipoles	24 × 5.2 m = 124.8 m	36 × 2.4 m = 86.4 m
Total quads	96 × 1.24 m = 119 m	48 × 0.5 m = 24 m
Beam pipe aperture	3 in × 5 in	2.8 in × 5.9 in
Max β function (m)	14.8 / 15.2	13.9 / 13.7
Max dispersion (m)	2.3	2.9
Transition γ	18.1	4.79
Beam intensity	7×10^{12}	2×10^{13}
Year constructed	TBD	1991
Construction cost	$60M (estimated)	$32M
Civil cost included?	No	Yes

Table 5-3 Comparison between the Stage 4 booster and the AGS Booster

6 Other Options

6.1 Booster Neutrino Beamline Option

After Stage 4 is complete, the old Booster is no longer needed. The present Linac can support pulse lengths in excess of 50 mS. The Linac pulse could be split by placing an additional electrostatic chopper in the 400 MeV line before the old Booster. A 40mA Linac beam pulse with a length of 50 mS contains 12.4×10^{12} particles which can supply 8.2×10^{12} protons to the Stage 4 booster and 4.2×10^{12} protons to the old Booster. Accelerating 4.2×10^{12} protons in the old Booster at a rate of 15 Hz can supply an 8 GeV proton beam at a flux of 21×10^{16} protons per hour.

6.2 20 Hz Acceleration Rate

Because of the lack of a transition crossing, the longitudinal emittance in Stage 4 might be well below 0.06 eV-sec per 53 MHz bunch. With this small of a longitudinal emittance, it may be possible to momentum stack five booster batches in the Accumulator. Momentum stacking five booster batches in the Accumulator at 15 Hz would require a Main Injector cycle time of 2.0 seconds which is the same flux as stacking four batches for a Main Injector cycle time of 1.6 seconds. However, the new Booster could be designed to run at a 20 Hz rate. Momentum stacking five booster batches at 20 Hz in the Accumulator would permit a Main Injector cycle time of 1.5 seconds. The proton flux would increase by 33 percent to provide enough protons for a 3.0 megawatt 120 GeV beam. The aperture requirements of the Stage 4 booster would remain about the same because the aperture is based mostly on peak intensity and is only weakly related to repetition rate.

7 Summary

After the collider program is concluded, the present antiproton production complex can be converted into a multi-stage proton accumulator which can supply enough protons for a 1.1 megawatt 120 GeV beam for a cost of about 12 million dollars. If driven by the physics needs to go beyond 1.1 megawatts, a new booster can be added in place of the Debuncher ring that can supply enough protons for a 2.3 megawatt 120 GeV beam for an additional cost of about 75 million dollars.

The proton accumulator is best thought of as extended stages of the present Proton Plan. Each stage is based on standard accelerator technology and accelerator parameters that are currently achievable. The schedule for each stage is driven by physics need and funding availability. Project staging has the distinct advantage of providing flexibility and a fraction of the total performance at a fraction of the total cost.

8 References

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"Antiproton and Neutrino Production Accelerator Timeline Issues," D. McGinnis, Fermilab Beams Document 1941, August 2005

[3] "Proton Driver Study II Part 1," G.W. Foster, W. Chou, E. Malamud, Fermilab TM-2169, May 2002